Cost Comparison for Deep Borehole Disposal as Alternative to Mined Repository - 24820

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Amentum

ABSTRACT

A comparison of projected costs for geologic disposal of high-level waste and spent nuclear fuel has been developed for the general categories of mined repositories and deep borehole disposal (DBD). Using published cost estimates from ten countries, this benchmarking study looks at a range of facilities and approaches within each category and generates a unit cost of disposal to allow comparison on an approximately consistent basis. Full life-cycle cost for disposal of appropriate packages in deep boreholes, normalized to the planned capacity of the facility, averaged 0.49 million dollars (MUSD 2023) per metric ton of heavy metal. The DBD projected costs were lower than the 1.07 MUSD/MTHM for mined repositories with comparably inclusive estimates.

Cost estimates were reviewed for mined repositories under consideration in the United States, Sweden, Slovenia, the United Kingdom, Finland, and Canada. For deep borehole disposal, costs were evaluated for facilities in the US, UK, Germany, Australia and a joint facility for members of the Association for Multinational Radioactive Waste Solutions (ERDO), a small-inventory European group which included Croatia, Denmark, Netherlands, Norway and Slovenia at the time of the study. Results of a published standalone comparison between a repository in Norway and a deep borehole alternative are also discussed.

The locations, size, capacity, and planned operating times vary significantly between the countries and the repository concepts. The estimates are based on conceptual designs and use generic geology assumptions. Accordingly, the cost estimates vary significantly in the level of detail and what activities are included. In addition, the process for evaluating and selecting a site and licensing the required facilities varies widely from country to country.

Cost estimates obtained from the published estimates were separated into the six phases of the facility life cycle: siting, licensing, construction, operations, closure, and post-closure monitoring.

INTRODUCTION

Geologic disposal has been identified by many countries as the preferred management approach for long-lived high-level waste (HLW). In many countries most, if not all, of the HLW consists of unreprocessed spent nuclear fuel (SNF). Countries with SNF reprocessing and/or nuclear defense programs will also have other waste streams that may require geologic disposal under their regulations or governmental policies. Traditionally, such disposal has been conceived as a mined repository that would offer flexibility for the size and form of the waste packages slated for disposal. This flexibility may be needed for some of the waste streams in countries with heterogeneous HLW forms. However, the SNF portion of the HLW inventory consists of long, thin assemblies that can be packaged in cylinders. Recent proposals suggest that such SNF containers could be managed through deep borehole disposal (DBD) which could offer operational and cost efficiencies.

This paper discusses the general features of the two disposal concepts and summarizes cost estimates that have been generated for facilities that would implement one of the two approaches.

Comparison of the costs indicates that there may be economic, social, and regulatory benefits to using DBD for the portion of HLW that the boreholes can physically accommodate.

DISPOSAL CONCEPTS

Geologic Disposal Facilities (GDFs) are being planned to allow safe management and disposal of the applicable waste streams. In some form and sequence, all concepts involve packaging of the waste, transport to the site, receipt at the facility, and handling or repackaging on the site. Which activities are to occur at the site or elsewhere may vary by a given country's infrastructure and the options available for a particular facility. Accordingly, inclusion of such costs, and the level of detail, varies significantly between facility approaches compared in this evaluation and their corresponding cost estimates.

Mined Repository

This "traditional" concept for a GDF is similar to an underground mine for coal or other resources. Such a facility would consist of several shafts for access and ventilation, an access tunnel to move package from the surface to the disposal level, and chambers for placement of the waste packages. Some preliminary designs include drilling holes in designated chambers for placement of high heat generating waste such as SNF. Disposal depths for the considered facilities is at least 300 meters below ground surface.

Deep Boreholes

As the name suggests, DBD involves drilling a hole of sufficient diameter to the desired depth and placing the waste packages in the bottom. The borehole could be vertical, or it could be started vertical and then directionally drilled with a large radius of curvature to reach horizontal at the intended disposal depth in an appropriate geology stratum. Waste packages manageable by DBD are limited by the geometry available by the borehole diameter and the curvature to reach the horizontal section. As such, the approach may be suitable for small waste packages or long, thin waste packages such as SNF. Disposal depths for the DBD concepts range from 1000 to 4750 meters below ground level.

COST COMPARISON METHODOLOGY

Comparison of cost estimates would be simple and more direct if the estimates followed a common work breakdown structure such as that suggested by the European Joint Programme on Radioactive Waste Management [1]. Such guidance tends to take a more thematic approach, recommending general, cross-cutting cost categories such as "stakeholder engagement", "program management" and "other actions/documents". The examples in the literature take a lifecycle approach that moves from site selection through licensing, construction, operation, and eventual closure of the repository and not enough detail is published in order to map these against the EURAD structure. For comparison purposes, we have therefore used a common structure aligned with the phased approach for iterative development of a geologic disposal recommended by the IAEA [2]:

1. Siting
2. Licensing
3. Construction
4. Operations
5. Repository closure
6. Post-closure monitoring

Within this structure, we have compared published costs for nine deep borehole repository and seven mined repositories concepts. Cost estimates obtained from the references are apportioned into the six phases of the facility life cycle. To provide a basis for comparison, the costs are converted to a common currency (US dollar) and inflated from the date of the estimate to 2023. The currency conversions use the average daily exchange rates for 2022 from the International Monetary Fund database [3]. The inflation data is from the European Central Bank [4].

The estimates are then normalized to the planned capacity of the borehole facility to allow an approximate equivalence for comparison. Dividing the total cost by the intended disposal capacity provides a normalized basis for comparison between countries and facility concepts and is expressed in our analysis in terms of million US dollars (MUSD) per Metric Ton of Heavy Metal (MTHM).

Assigning cost to one of the six phases is not an exact science and has been done with the intent to balance the information provided in the source documents with the different approaches for each facility. For example, in the Yucca Mountain approach post-emplacement monitoring occurs prior to final closure, so those cost are included under "Closure" [5]. As a result, the line item for "Post-Closure" is empty. However, for Sweden [6] and some of the DBD concepts the Post-Closure costs are called out separately.

Because only a few of the estimates included transportation from the generator to the disposal facility, such costs have not been included in these summaries. The impact of the cost of transporting the waste is considered later in this paper.

ANALYSIS

The locations, size, capacity, and planned operating times vary significantly between the countries and the repository concepts. The estimates are based on conceptual designs and use generic geology assumptions. Accordingly, the cost estimates vary significantly in the level of detail and what activities are included. In addition, the process for evaluating and selecting a site and licensing the required facilities varies widely from country to country. These costs are understood to be generally independent of the quantity of material that will be disposed. Such costs can be considered fixed. Some of the construction costs are also mostly independent of the quantity of material, such as the infrastructure and above ground facilities. Construction of the below ground facilities, site operations and below-ground closure costs will vary with the quantity of material and the associated operational time.

The following sections break out the DBD and mined repositories and provide a brief description of each conceptual facility in order to give context to the different estimates.

Deep Borehole Repositories

Nine studies were selected for comparison because they are recent (i.e., all undertaken within the last twelve years), they use a formal Work Breakdown Structure and are highly relevant in that they focus on disposal of spent fuel and/or high-level waste (rather than, for example, nearer-surface disposal of sealed sources). The parameters for each study are summarized in Table 1. The facilities were generally proposed under different criteria using different assumptions, so costs were not always assigned for one or more phases. Several cost estimates were focused on a limited scope, such as borehole drilling and construction for the Australia or Sandia facilities, and are evaluated with those limitations in mind.

Table 1. Summary of Deep Borehole Disposal Studies

#	Country	Study Author	Full Life Cycle?	Repository Concept
1	Norway	AINS Group for Norwegian Nuclear Decommissioning (NND) [7,8]	Yes	A 2020 study for Norwegian Nuclear Decommissioning (NND) conceived a single crystalline borehole for research reactor waste as a stand-alone deep borehole disposal facility (DBD) with a borehole depth of 3500 meters, using the lowest 500 meters for disposal of the waste packages. The base capacity of high-level spent fuel for the conceptual design and cost estimate is 16.5 tons in 69 BSK canisters. This is a very low amount of waste for a stand-alone facility relative to most other national facilities. This results in a high unit price as measured by cost divided by disposed metric tons of heavy metal (MTHM). The study by the AINS Group builds on previous work on a conventional mined repository and is more detailed than many of the other national studies.
2	UK	Gibbs et al [9]	Yes	A 2021 study by experts from the University of Sheffield and the UK drilling industry on application of DBD in the UK estimated that 7 to 10 boreholes would be needed to dispose of the expected 3200 MT of reprocessed spent fuel. The cost estimate for 10 boreholes is based on shallower depths of 4250 m as compared to another 500 meters deeper for the 7-borehole model. The cost estimate for the 10-hole DBD covers most cost items. While it does include costs for a safety case and for some facilities for a test borehole, it specifically does not include the costs for selecting and obtaining approval for a host site.
3	Germany	Bracke et al [10]	Yes	A concept for a German DBD facility was done with general approximations. The cost estimate was based on 35 boreholes to a depth of 3500 meters. The number of boreholes was based on the needed capacity for 10,500 MT of vitrified High-Level Waste. This waste form is wider (outer diameter of 43 cm) than most of the other waste forms considered in other studies, so drilling costs are higher to deliver wider boreholes.
4	US	EPRI [11]	Yes	The Electric Power Research Institute (EPRI) performed a study based on using DBD at the site of potential advanced reactors in the US, assuming that each reactor would generate 1000 MTHM over 20 years. The costing was based on a borehole 1 km deep and 1.5 km horizontally in a sedimentary rock such as shale. The report provides the cost estimate as a total without breaking down the component costs except for a line item for mobilization and demobilization of the drilling equipment.
5	US	SNL [12]	No	Sandia National Laboratory (SNL) developed a reference design and cost estimate for drilling and operations at a single borehole with a capacity of 253 MTHM. However, they state that the "cost estimate is for a full-sized disposal borehole, but without the logging and testing of the initial borehole at a site. As such, this estimate and the associated total cost correspond to the incremental costs of an additional borehole at an existing, approved site for deep borehole disposal." Based on the focus of the SNL study the cost estimate can be considered relevant to comparison with the marginal or variable costs of other estimates.
6	Australia	CSIRO [13, 14]	No	The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia generated cost estimates for drilling large diameter boreholes suitable for DBD (similar to the German study). Of several options evaluated by CSIRO, this paper discusses the cost for a borehole 3 km deep in shale as most comparable to the other studies. The Australian cost estimate only includes costs directly related to the drilling, and not any program or disposal costs. The estimate is only relative to the borehole construction. The cost per MTHM is based on the quantity a borehole of that size could possible accept (21.3 MTHM).
7	US	Deep Isolation [15]	Yes	In 2019 Deep Isolation worked with supply chain partners and advisers including Bechtel, NAC International and Schlumberger (now SLB) to estimate the cost of disposing all US spent fuel in deep boreholes. The disposal concept was based on 10 regional sites with 220 boreholes per site, with each site requiring a license. The total amount of spent fuel disposed is 151,754 MTHM. Boreholes would average 1 km deep and 1.5 km in horizontal length.
8	ERDO (Croatia, Denmark, Netherlands, Norway and Slovenia)	Deep Isolation, for NND (commissioning on behalf of ERDO) [16]	Yes	The European Repository Development Organisation (ERDO) DBD repository concept developed by Deep Isolation would use boreholes 1.5 km deep with 1.5 km horizontal sections. Capacity is 1794 MTHM (all high heat generating waste and long-lived ILW across the ERDO countries) managed in 2,486 standard canisters in 12 standard boreholes and 360 large canisters in 2 large boreholes at a single site in sedimentary rock. Siting and licensing costs are shown as one combined line item.
9	UK	Deep Isolation, for the Nuclear Decommission-ing Authority (NDA) [17]	Yes	The Deep Isolation concept and estimate for the UK includes disposal of all High Heat Generating Waste at a single site in shale geology. Similar to the other Deep Isolation generic concepts, boreholes would be 1.5 km deep with 1.5 km horizontal sections. The cost estimates developed include all facility life cycle costs except for post-closure costs, which are excluded based on national policy. Siting and licensing costs are shown as one combined line item.

General Discussion – DBD

The detail and break out of costs varied widely for each facility, and most estimates were not structured cleanly by phase of development. Table 2 illustrates the high-level Work Breakdown Structure (WBS) used in the nine practical cost studies reviewed for DBD concepts. Examination of those WBS's in shows the range of costs considered for each facility. To provide an understanding of the extent of each estimate, the estimated costs were assigned to one of the six development phases listed above.

Table 2. Examples of top-level Work Breakdown Structures (WBS) for Geologic Disposal

1. Norway (AINS Group) [7,8] • Siting and licensing • Site investigation • Investment and construction • Operations • Closure	**2. UK** (Gibb et al.) **[9]** • Surface works • Borehole construction • Overpacking • Transport • Package emplacement • Sealing	**3. Germany** (Bracke et al.) [7] • Facility demonstration • Site selection and exploration • Borehole • Containers • Reconditioning • Installation and operating cost • Licensing/safety analyses	
4. US (EPRI) [11] • Base disposal • Mobilization and demobilization • Storage during AR operation • Storage after AR shutdown	**5. US** (Sandia National Laboratory) [12] • Drilling, casing and borehole completion • Waste canisters and loading • Waste emplacement • Operations and materials • Borehole sealing operations and materials	**6. Australia** (CSIRO) **[**13, 14] • Planning and approval • Site preparation • Drilling and completion	Deep Isolation cost studies for: **7. US** [15] **8. ERDO (Croatia, Denmark, Netherlands, Norway, Slovenia) [16]** **9. UK** [17] • Siting and licensing (broken out as separate items in the US study) • Construction • Operations • Repository closure • Post-closure monitoring

Among the nine DBD studies, the three by Deep Isolation and the AINS study for Norway are the most detailed and comprehensive in their cost analysis, and closest in their cost breakouts to the WBS format recommended by EURAD. Conversely, the Australian study only estimates the cost of drilling the borehole and the Sandia estimate is a Reference Design borehole based on an "nth" borehole at a given site and does not include any program or infrastructure costs. The UK study does not include cost for site selection. Similarly, the US study by EPRI assumed that the disposal borehole would be co-located with an advanced reactor and therefore does not include any separate costs for siting. The German study includes general, order-of-magnitude costs through final emplacement.

For those estimates that include them, licensing costs vary by almost an order of magnitude across countries and are a significant driver of the overall cost uncertainty. The nature of site selection processes and regulatory requirements makes the costs inherently difficult to forecast. Given that and the variation in regulatory environments between countries leads to the situation where it is challenging to evaluate the realism of the costs and hard to compare across borders.

DBD Cost Estimates

Summaries of the cost estimates for the DBD concepts, broken out by phase, are provided in Table 3. The costs have been converted to 2023 US Dollars using the methodology described above.

Table 3. Borehole Disposal Cost Comparisons in Published Cost Studies

	1. Norway (AINS)	2. UK (Gibb et al)	3. Germany (Bracke et al)	4. US (EPRI)	5. US (Sandia)	6. Australia (CSIRO)	7. US (Deep Isolation)	8. ERDO (Deep Isolation)	9. UK (Deep Isolation)
Siting	28	-	1,975	-	-	-	211	113	99
Licensing	13	15	230	-	-	1	513		
Construction	116	1,253	3,753	-	38	23	25,692	255	2,145
Operation	34	187	5,926	582	14	-	35,329	254	1,551
Closure	24	63	-	11	3	-	2,916	23	269
Post-closure	-	-	-	-	-	-	507	44	-
TOTAL	**215**	**1,518**	**11,886**	**593**	**55**	**24**	**65,170**	**690**	**4,063**
Capacity (MTHM)	17	3,200	10,500	1,000	253	21	151,754	1,794	7,438
Cost per MTHM (million USD)	**13.01**	**0.47**	**1.13**	**0.59**	**0.22**	**1.15**	**0.43**	**0.38**	**0.55**

Seven of the studies provide "full lifecycle estimates" – Norway, UK DBD, Germany, EPRI, and the three by Deep Isolation. Looking at the normalized unit costs per MTHM disposed (bottom row of Table 3) it is apparent that the Norway estimate is anomalous relative to the other DBD cases. The facility is conceived as just a single borehole for a limited waste quantity. This results in a large proportion of fixed cost for siting, design, and construction, with limited inventory volumes to amortize the cost over.

Excluding Norway, a comparative analysis shows that the average unit cost for the other six studies is 0.59 MUSD per MTHM. Of these, the estimate for the German facility looks to be an outlier, with a unit cost about twice that of the next highest rate. Averaging the remaining five full lifecycle programs yields a unit cost for disposal of 0.49 MUSD/MTHM.

The single borehole options present a significant difference in cost estimates. The SNL Reference Design borehole is estimated based on an "nth" borehole at a given site and does not include any program or infrastructure costs. It is representative of the marginal cost of an additional borehole at an existing site. In comparison, the CSIRO estimate for Australia includes planning and approval for the borehole. The study acknowledges that additional boreholes would be less expensive since approximately one-third of the cost is for the mobilization and demobilization of the drilling rig. The Australia study does not quantify the disposal capacity so the unit cost is based on an estimate of the amount of material (100 CSD universal waste canisters) that could be placed in a borehole with a 76" diameter at the bottom.

The average unit cost of the three Deep Isolation estimates (US, ERDO, and UK) is 0.45 MUSD per MTHM. Though these three used a common estimating approach, differences in assumption on facilities and geologies resulted in a range in the estimates. While the US estimate is based on 10 regional sites with multiple boreholes and the UK and ERDO facilities assume a single site each, the US study incorporates a benefit of scale based on common portions of the design and licensing efforts.

The other two sites with "full cycle" estimates (UK and EPRI) average 0.53 MUSD per MTHM. Note that while the EPRI study only contains two line items, that is because the estimate was presented as a lump sum and did not breakout the costs that it states are included.

In general, the full program estimates by Deep Isolation for the US, ERDO, and the UK are comprehensive in their inclusion of all life cycle costs and describe a costing methodology involving extensive supply chain engagement. Those estimates provide a reasonably well-defined cost basis for each facility, and one that is at an appropriate level of detail for cost assessment at the generic design stage of IAEA's phased approach to repository development [18].

Mined Repositories

Seven studies were selected for comparison based on the availability of cost data and comparable design features. The facilities are slated for disposal of spent fuel and/or high-level waste, though several are associated with disposal capacity for disposal of a broader range of radioactive waste streams. With the exception of the Yucca Mountain estimate from 2007 [5], the studies have all been published within the past 5 years. The parameters included in each study are summarized in Table 4. The studies were performed under different auspices and thus generated estimates to varying levels of detail. While most address a full life cycle for the subject facility, others did not include one or more phases based on the status of the project, as summarized in Table 5. For example, the costs for Finland are from the license application by the utility consortium for a specific site, so costs for site characterization and selection are past expenses and the licensing costs are not relevant to the submittal [19]. Levels of detail and the basis of estimate were generally developed and proposed under different criteria using different assumptions, so costs were not always assigned for one or more phases. Yucca Mountain, in comparison, was a government project that includes previously incurred costs along with the forecast cost at the time.

General Discussion – Mined Repositories

Mined repositories are intended to provide capacity for all of a given entity's inventory requiring deep geological disposal. The quantity and form of such radioactive wastes varies significantly between the entities. While US and the United Kingdom have a range of spent fuel, high level wastes, and related defense wastes, the other countries are primarily dealing with spent fuel as requiring a GDF. Dealing with a single waste stream and form simplifies the design and operations plans. However, there are significant upfront costs that are relatively independent of the size of the waste streams, such as site selection, licensing, and infrastructure construction. For facilities with relatively small quantities of waste to be disposed, these can be a significant fraction of the overall disposal cost.

Finland has progressed the furthest towards operation of a spent fuel disposal facility with submission in 2021 of a license application for a specific site. The application provides details on the expected disposal inventory. Costs are projected for construction, operations, and decommissioning over a 100-year span but do not include past and future costs for pre-implementation and in-service research work, administration, taxes and regulatory oversight.

Sweden has an ongoing radioactive waste management program with active disposal facilities. The spent fuel repository will be developed adjacent to the existing facilities to take advantage of existing infrastructure. Projected costs for the repository have been excerpted from the overall waste management reference scenario, with 25% of the central function cost allocated to the spent fuel category in this comparison.

Table 4. Summary of Mined Repository Concepts in Cost Benchmark Study

#	Country	Study Author	Full Life Cycle?	Repository Concept
1	US	DOE [5]	Yes	The 2007 report by the Department of Energy updated the 2001 estimate to provide a basis for assessing the adequacy of the Nuclear Waste Fund (NWF) Fee. The estimate includes both historical costs and costs projected through decommissioning of the repository in 2133. Transportation related costs are not included so as to be more comparable to other studies. Yucca Mountain was planned to accommodate 122,100 MTHM in about 17,450 packages.
2	Sweden	SKB [6]	Yes	A 2022 study by Svensk Kärnbränslehantering AB (SKB), the company owned by the for the nuclear power plant licensees, to comply with regulations requiring preparation of a cost estimate of all measures needed to manage and dispose of the nuclear fuel used in the reactors and other radioactive residual products. The Spent Fuel Repository is designed for approximately 5600 canisters of spent fuel, totaling 11,267 MTHM. The deposition areas will be located about 470 metres below the ground level. Costs are based on the reference scenario and do not include the repositories for short- and long-lived wastes. SKB central functions are assigned 25% to the Spent Fuel Repository.
3	Norway	AINS Group, for Norwegian Nuclear Decommissioning (NND) [7,8]	Yes	A 2020 study for Norwegian Nuclear Decommissioning (NND) considered the case of a stand-alone deep geologic repository for spent research reactor fuel at a depth of about 400 meters with individual deposition holes. The study by the AINS Group builds on previous work for a single national facility that would include disposal of very low, low- and intermediate-level waste, and non-radioactive decommissioning waste. The base capacity of high-level spent fuel for the conceptual design and cost estimate is 16.5 tons in 28 KBS-3 canisters. This is a very low amount of waste for a stand-alone facility relative to most other national facilities. This results in a high unit price as measured by cost divided by disposed metric tons of heavy metal (MTHM).
4	Slovenia / Croatia	IBE [20]	Yes	A 2019 study to update costs estimates was part of the basis for determination of the radwaste management fee charged to power utilities. The generic hard rock site would accommodate 2282 fuel elements conditioned in 571 disposal canisters to be disposed at a depth of about 500 meters during 10 years of repository operation. Costs include VAT but no contingency. The facility is to be developed as a collaboration between Slovenia and Croatia based on the shared ownership of the Krško nuclear power plant.
5	UK	NWS [21]	Yes	The UK NDA Nuclear Waste Services organization annual report for 2020 – 2021 provided estimates of the total lifecycle GDF cost for different combinations of minimum and higher risk costs and lower and higher geologic complexity using the current projected waste inventory. Another set of cost estimates was provided for the inventory plus the addition of spent fuel, uranium, and plutonium wastes. The full inventory included 23, 326 MTHM.
6	Finland	Posiva Oy [19]	Yes	The 2021 license application for the ONKALO encapsulation and disposal facility indicated that approximately 6,500 MT uranium in spent fuel would be disposed in 3,300 canisters. Disposal would be in granite bedrock at a depth of about 450 meters. The costs cited in the application do not include siting or licensing.
7	Canada	NWMO [22]	Yes	The 2021 report by the Nuclear Waste Management Organization (NWMO) was based on disposal of 5.5 million bundles of spent fuel in crystalline rock at a depth of 500 meters. Transportation related costs are not included so as to be more comparable to other studies.

Table 5. Examples of Top-Level WBS for Mined Geologic Disposal

1. US - Yucca Mountain (USDOE) [5] • Development & Evaluation • Eng, Procurement, and Construction • Operations • Monitoring • Closure	**2. Sweden** (SKB) [6] • Clab • Encapsulation • Spent Fuel Repository • SKB central functions	**3. Norway** (AINS Group) [7, 8] • Investigation Phase • Above Ground Facilities • Safety Case (one municipality) • Underground Facilities
4. Slovenia (IBE) [20] • Siting, Project admin, R&D, site purchase • Investment and construction – On-site disposal • Investment and construction – Encapsulation plant • Operation and maintenance – Disposal • Operation & Maintenance – Above ground facilities • Decommissioning and closure • Compensation costs	**5. United Kingdom** (NWS) [21] • Life cycle total cost **6. Finland** (Posiva Oy) [19] • Construction • Operations • Decommissioning and closure	**7. Canada** (NWMO) [22] • Siting • Characterization & Licensing • Construction • Operations • Monitoring • Decommissioning and closure

The Canadian estimate was prepared by Nuclear Waste Management Organization (NWMO) based on a projected used fuel inventory of 5.5 million used CANDU fuel bundles. While the site selection process is ongoing, the cost estimate was developed using the bounding scenario for geology and location of having the repository in the crystalline rock of northwest Ontario.

The cost estimate for the Yucca Mountain project in the US was last formally updated in 2007. The project has essentially been abandoned as the US Government has not provided any funding for the project since 2010.

The UK is in a process to site and develop a GDF for disposal of Intermediate Level Waste, High Level Waste, spent fuel, and various uranium and plutonium wastes. The UK's Nuclear Decommissioning Authority's Nuclear Waste Services organization (NDA/NWS) published an annual report for 2020 - 2021 with several scenarios for costs of a GDF, with ranges of waste inventories and different assumptions for the disposal geology. The baseline estimates did not include disposal of spent fuel and plutonium because such materials "are not currently classified as waste" in the UK. Scenarios with "full potential inventory" included the legacy wastes and "new nuclear and nuclear materials that could be categorized as waste in the future, such as unreprocessed spent fuel". These costs were presented as single point values for each scenario without detailed breakdowns. The estimate for the cost is generated by averaging full inventory estimate for each scenario. A separate calculation of costs is performed by allocating 75% of total cost to SNF and HHGW disposal, allowing the 25% discount for the ILW disposal.

Mined Repository Cost Estimates

Summaries of the cost estimates from seven repository studies, broken out by phase, are provided in Table 6. The costs have been converted to 2023 USD using the methodology described above.

Not all studies included or identified transportation costs. Where waste transportation was detailed, it has been removed from the estimate and is discussed separately below.

The mined repository estimates generally cover the full life cycle of the facility. Finland is the exception, with the site selection and licensing costs not included in the submitted license application. However, the overall estimate for the rest of the scope is likely to be the best since it is for a current project for a specific site and defined design.

As discussed regarding the DBD disposal cost, the estimated unit disposal cost for the Norway facility (27.8 MUSD/MTHM) is much higher than in other studies which ranged from 0.22 to 2.34 USD/MTHM. While the Norway estimated cost is the lowest among the pool, the small inventory slated for the facility results in the high unit cost. The average for the six other estimates is 1.07 MUSD/ MTHM. The UK facility estimated cost of 2.34 MUSD/MTHM is about double the average due to the high construction costs relative to the waste quantity. Discounting the UK estimate by 25% to account for ILW-related costs, presuming disposal at shallower depths with less mining, gives an average unit cost for the six studies of 0.98 MUSD/MTHM.

Table 6. Mined Repository Disposal Cost Comparisons in Published Cost Studies

<table>
<tr><th>Facility</th><th>Yucca Mountain</th><th>Sweden</th><th>Norway Repository</th><th>Slovenia / Croatia Repository</th><th>UK GDF</th><th>Finland</th><th>Canada DGR</th></tr>
<tr><td>Siting</td><td>16,664</td><td>-</td><td>28</td><td>192</td><td rowspan="6">54,509
(40,882)</td><td>-</td><td>1,166</td></tr>
<tr><td>Licensing</td><td>25,346</td><td>1,059</td><td>10</td><td>382</td><td>-</td><td>1,802</td></tr>
<tr><td>Construction</td><td>28,325</td><td>4,067</td><td>228</td><td>368</td><td>1,070</td><td>4,114</td></tr>
<tr><td>Operation</td><td>25,540</td><td>3,090</td><td>98</td><td>364</td><td>3,279</td><td>12,746</td></tr>
<tr><td>Closure</td><td>17,170</td><td>759</td><td>94</td><td>66</td><td>134</td><td>3,544</td></tr>
<tr><td>Post-Closure</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>TOTAL</td><td>113,045</td><td>8,975</td><td>459</td><td>1,372</td><td>54,509</td><td>4,482</td><td>23,371</td></tr>
<tr><td>Capacity (MTHM)</td><td>122,100</td><td>11,300</td><td>17</td><td>926</td><td>23,326</td><td>6,500</td><td>106,000</td></tr>
<tr><td>Cost per MTHM (million USD)</td><td>0.93</td><td>0.79</td><td>27.80</td><td>1.48</td><td>2.34
(1.75)[1]</td><td>0.69</td><td>0.22</td></tr>
</table>

[1] UK GDF – (cost) reflects 25% allowance for disposal of ILW

The Canada facility estimate of 0.22 MUSD/MTHM is about 20% of the average unit cost. Part of this difference is attributable to the low siting and licensing costs with those line items comprising about 13% of the cost versus an average of 40% for the US and Slovenia/Croatia facilities. However, even if the cost of the program were to double it would still be less than half the unit cost of the average for the other estimates. Taking the five studies other than Norway and the UK, the average disposal cost is 0.82 MUSD/MTHM. Removing the low Canada estimate as well leaves the remaining four site estimates at an average of 0.97 MUSD/MTHM. The average cost of the YM, Sweden, Slovenia/Croatia, Finland, and discounted UK facilities (i.e., dropping Canada) is 1.13 MUSD/MTHM.

TRANSPORTATION

While not included in the general estimates discussed above, transportation of the wastes from the generator location to the disposal site could represent a significant cost. For a centralized facility with waste shipments coming from relatively far-flung sites the infrastructure, transport casks, emergency responder training along all possible transportation routes, and the associated handling and maintenance would be more expensive than with smaller programs with limited inventory and shorter haul lengths. Regional facilities would reduce travel distances but would require multiple regulatory programs for siting and licensing of the facility plus additional infrastructure development.

Table 7 shows the costs estimates contained in the studies for several of the mined repositories. As with the cost estimates for the repositories themselves, what is included in the transportation category varies between the estimates. A significant difference is that the Transport, Aging, and Disposal (TAD) canisters are included as a transport cost for US Yucca Mountain, but the disposal canisters are part of operations for the Canada estimate. For Yucca, this is $14B of the $30B transportation estimate, or about $0.12 MUSD/MTHM, about half of the total nominal transportation cost. The operations estimate for Canada includes 4,000 MUSD for the Used Fuel Containers, which is about $0.038 MUSD/MTHM. That compares to the $0.014M USD/MTHM categorized as transportation in the Canada estimate by NWMO.

Table 7. Transportation Cost Comparison

Facility	Est Costs (million)	Currency	Year	MTHM	MUSD 2023	MUSD/ MTHM
Yucca Mountain	20,250	USD	2007	122,100	$ 30,156	$ 0.247
Canada	1,539	CAD	2020	106,000	$ 1,469	$ 0.014
Sweden	4,100	SEK	2022	11,300	$ 446	$ 0.039
Slovenia	4.68	EUR	2018	926	$ 6	$ 0.007

Overall, transportation costs for the US GDF at Yucca Mountain are substantially higher on a per unit cost than the other sites. The US approach assumes rail transport to the disposal facility while the other countries incorporate truck transport. The estimated cost for the Nevada infrastructure portion alone of the transport scheme is 4,000 MUSD, about 170% more than the entire estimate for the Canada approach. The Canadian Adaptive Phased Management approach (APM), however, only involves moving used fuel from interim storage sites to the repository location. The much longer distances involved in the US and higher costs for the casks and canisters for the light water reactor spent fuel are also significant cost factors relative to the other sites. While Canada is much larger geographically than Sweden and Slovenia and comparable to the US, the transport distances are forecast to be much less than in the US, on the order of 1000 miles, since 90% of the projected inventory will be generated in the same province (Ontario) as the disposal facility.

The expected inventory for the Canadian facility is comparable to that of the US (87% based on MTHM) but overall transport costs are about 6%. The unit transportation costs in the Sweden and Slovenia estimates are similarly low. Even if the canister costs are allocated to the repository rather than be under transportation, the rail-based transport for Yucca is an order of magnitude greater in cost than the truck-based transport for the smaller distances in the other estimates.

CONCLUSIONS

The needs and opportunities for geological disposal can vary significantly between countries and regions depending on the waste streams and the available geologies. In addition, the cost studies for the various facilities were developed for different reasons and were based on different levels of detail. Thus, individual estimates cannot be directly compared. Looking at the ranges and averages of the estimates offers an insight to the relative costs of mined repositories versus deep boreholes.

Apart from the anomalously high value for the small capacity Norway facility, the unit costs for six estimates for mined repository disposal ranged from 0.22 to 2.24 MUSD/MTHM, with an overall average of 1.07 MUSD/MTHM. In comparison, the full life cycle estimates for six deep borehole facilities ranged from 0.38 – 1.13 MUSD/MTHM, with an average of 0.59 MUSD/MHTM. Leaving out the outlier high estimate, the range becomes 0.38 – 0.59 MUSD/MTHM, with an average unit cost for disposal of 0.49 MUSD/MTHM.

The estimates show that the lowest estimate for a mined repository (Canada at 0.22 MUSD/MTHM) is less than the lowest DBD estimate (ERDO at 0.38 MUSD/MTHM). The highest of the five detailed DBD estimates (EPRI at Advanced Reactor sites at 0.59 MUSD/MTHM) is less than the second lowest mined repository estimate (Finland at 0.69 MUSD/MTHM).

A particular comparison that is noteworthy is that between the estimates for the Norway repository and the Norway borehole. They were made at the same time using a common basis for site conditions, disposal quantity, and operations. The unit costs for disposal in either concept are much higher than other facilities due to the small amount of waste needing disposal.

The unit cost for disposal estimated for the Norway mined repository was 26 MUSD/ MTHM, as compared to 12 MUSD/MTHM for the DBD concept.

These comparisons lead to the following observations:

- Mined repositories are necessary for managing legacy waste streams that would be hard or prohibitively expensive, if possible at all, to repackage to make suitable for disposal in a borehole.
- Deep borehole disposal is likely to be less expensive for countries where the entire waste stream is suitable for DBD. Based on examining the cost for each phase, the savings would be derived from significantly less underground construction.
- The UK GDF cost estimate shows a significant difference in marginal cost for the deeper disposal of the spent fuel, uranium, and plutonium waste streams. The DBD costs for disposal of such streams appear to be significantly less than the NWS estimates for expanding the mined repository to accommodate them. This is an area for consideration for facilities contemplating management of multiple waste streams at one location, such as Sweden, United Kingdom, and France. Depending on the cost of deep excavation and underground operations, DBD of appropriate waste forms may be less expensive than the additional mining that would be needed.
- In addition to the marginal cost savings in actual disposal, the ability to dispose of SNF in shorter time frames could offer substantial savings in reduced storage and maintenance efforts.
- The rail transportation system envisioned to support the Yucca Mountain disposal operations is estimated to be much more expensive than the truck-based transport systems planned elsewhere. It is important to note that within the US, rail transport was considered to be the most economical mode of shipment to a repository, so any future repository anywhere within the US will most likely require rail and be a significant cost driver. Consideration of transport cost and logistics should be considered in site selection. The DBD concept with regional facilities in the US would potentially offer a cost benefit in reduced transportation.

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